

NASA's Optical Measurement Program 2014

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ABSTRACT

The Optical Measurements Group (OMG) within the NASA Orbital Debris Program Office (ODPO) addresses U.S. National Space Policy goals by monitoring and characterizing debris. Since 2001, the OMG has used the Michigan Orbital Debris Survey Telescope (MODEST) at Cerro Tololo Inter-American Observatory (CTIO) in Chile for general orbital debris surveys. The 0.6-m Schmidt MODEST provides calibrated astronomical data of GEO targets, both catalogued and uncatalogued debris, with excellent image quality. The data are utilized by the ODPO modeling group and are included in the Orbital Debris Engineering Model (ORDEM) v. 3.0. MODEST and the CTIO/SMARTS (Small and Moderate Aperture Research Telescope System) 0.9 m are both employed to acquire filter photometry data as well as synchronously observe targets in selected optical filters. Obtaining data synchronously yields data for material composition studies as well as longer orbital arc data on the same target without time delay or bias from a rotating, tumbling, or spinning target.

Observations of GEO orbital debris using the twin 6.5-m Magellan telescopes at Las Campanas Observatory in Chile for deep imaging (Baade) and spectroscopic data (Clay) began in 2011. Through the data acquired on Baade, debris has been detected that reaches ~3 magnitudes fainter than detections with MODEST, while the spectral data from Clay provide better resolved information used in material characterization analyses.

To better characterize and model optical data, the Optical Measurements Center (OMC) at NASA/JSC has been in operation since 2005, resulting in a database of comparison laboratory data. The OMC is designed to emulate illumination conditions in space using equipment and techniques that parallel telescopic observations and source-target-sensor orientations.

Lastly, the OMG is building the Meter Class Autonomous Telescope (MCAT) at Ascension Island. The 1.3-m telescope is designed to observe GEO and LEO targets, using a modified Ritchey-Chrétien configuration on a double horseshoe equatorial mount to allow tracking objects at LEO rates through the dome's keyhole at zenith.

Through the data collection techniques employed at these unique facilities, NASA's ODPO has developed a multi-faceted approach to characterize the orbital debris risk to satellites in various altitudes and provide insight leading toward material characterization of debris via photometric and spectroscopic measurements. Ultimately, the data are used in conjunction with in-situ and radar measurements to provide accurate data for models of our space environment and for facilitating spacecraft risk assessment.

1. Introduction

NASA's Orbital Debris Program Office (ODPO) is located at NASA/Johnson Space Center (JSC). The ODPO is comprised of various teams including measurements, modeling, protection, mitigation and reentry. This paper will focus on the current optical measurements assets in use by ODPO. For the past decade, the main region for optical detection and analysis has been the Geosynchronous Orbit (GEO), using various telescopes in Chile. The statistical survey data have been used to supply the Orbital Debris Engineering Model (ORDEM) v. 3.0 with actual detections in GEO. Photometric and spectroscopic data have also been acquired using various Chilean telescopes to better determine the surface composition of known (as a baseline and system confirmation) and unknown debris. The remotely collected data are used in comparison to laboratory data, which consists of photometric and spectroscopic data of spacecraft materials. In order to best simulate the orbital debris population, three main sources are used as test fragments for laboratory optical measurements: flight-ready materials, destructive hypervelocity testing (simulating on-orbit collisions), and destructive pressure testing (simulating on-orbit explosions). The NASA ODPO will soon break-ground for a new optical asset that will not only survey and track targets in the GEO region but is capable of tracking targets at much faster rates found in the Low Earth Object (LEO) regime for low inclinations. This paper will discuss each of NASA's ODPO optical assets and how the data are used in conjunction with in-situ

and radar measurements to provide accurate data for models of our space environment and service spacecraft risk assessment.

2. Michigan Orbital DEbris Survey Telescope (MODEST)

2.1 MODEST: survey data

NASA has utilized the 0.61-m aperture Curtis-Schmidt telescope located at Cerro Tololo Inter-American Observatory (CTIO) in Chile to help characterize the debris environment in the geosynchronous region since 2001. The 0.6-m Schmidt MODEST provides calibrated astronomical data of GEO targets, both catalogued targets (CTs) and uncatalogued targets (UCTs), with excellent image quality. As of 2010, MODEST employs a 4Kx4K Spectral Instruments (SI) CCD optical camera with a suite of filters, including a broad R filter specifically designed to maximize the signal to noise ratio for orbital debris detections. MODEST is able to detect objects as faint as 18th magnitude (R filter) using a 5 second exposure. This corresponds to a 20-cm diameter, assuming a 0.175 albedo object at 36,000 km altitude that follows a Lambertian phase function. From 2001 to date, MODEST has served as NASA's primary optical detector for statistically surveying the GEO region to provide flux estimates for the number of detected objects. These detections are sorted by correlated targets, objects that are found in the U.S. Space Surveillance Network catalog, and uncorrelated, objects not cataloged. These data are used to contribute to orbital debris engineering models, such as ORDEM 3.0, resulting in better environmental models that incorporate real data for uncatalogued objects.

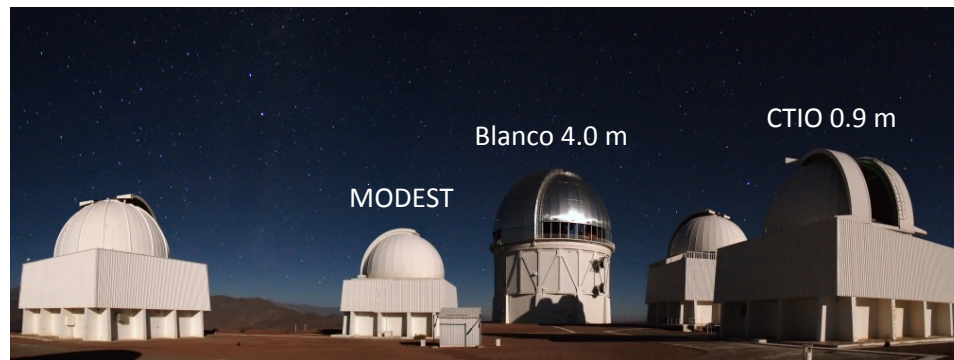


Fig. 1. Panoramic view of CTIO, courtesy of www.ctio.noao.edu/

Fig. 2 shows published Inclination (INC) versus Right Ascension of Ascending Node (RAAN) data for MODEST observations from 2004-2009. The blue ‘.’s indicate CT objects detected and the red ‘x’s symbolize UCTs [1, 2]. The dots and x’s are not necessarily unique objects but rather the location of an object when it was observed. It is possible that one object is represented by more than one dot or x. The data represents 42, 23, 35, 36, 43, and 43 nights of data respectively for each progressing year (2004-2009). The plots below are useful for identifying potential clusters of unknown breakups. For example, centered near 330° RAAN and 10° INC is a cluster of UCTs and CTs associated with the 1992 Titan IIIC Transtage (1968-081E; SSN 3432) breakup.

Although limited datasets of survey data has been collected after 2009, the data are still being analyzed and will be presented in the next MODEST report, 2010-2014. The type of data collected also changed starting in 2010 and will be discussed in Section 2.2 and 2.3

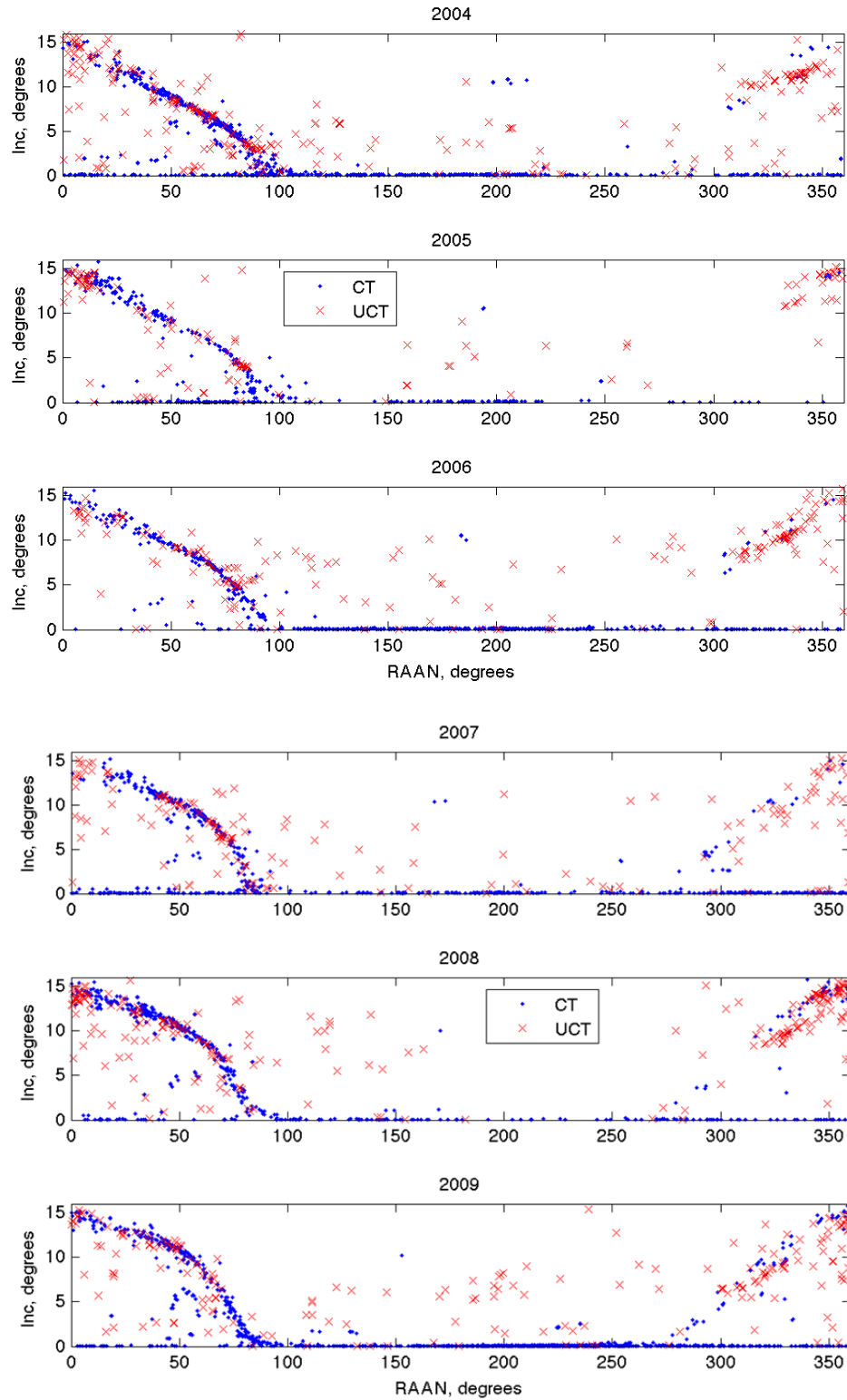


Fig. 2. Inclination versus Right Ascension of Ascending Node for MODEST observing 2004-2009 [1, 2].

2.2 Photometry: Synchronous

Photometric measurements using MODEST have been on-going for several years, sometimes in conjunction with the CTIO Small- and Medium-Aperture Research Telescope System (CTIO/SMARTS) 0.9-m telescope. Initial operations using MODEST and 0.9-m included survey and chase where MODEST would first detect the target, the positional data were sent to an in-house developed orbit propagator, and objects were tracked to acquire longer orbital arcs to better refine the orbital information, especially the eccentricity which is initially assumed to be a circular orbit given the limited time the object is in the MODEST field-of-view (approximately five minutes).

Once the orbit was determined to have high confidence for long orbital arc tracking within the small 0.22° field of view of the 0.9-m, photometric data could be obtained. Due to the nature of a tumbling object, potentially with very short tumble rates and irregular shape/composition, synchronous observational data is the key to truly understanding surface material composition using filter photometry instrumentation to ensure that the return signal for both filters represents the same facet of the object. Thus, MODEST and CTIO 0.9-m were electronically synchronized to within 50 ms to observe the same target in the R filter and B filter respectively. Fig. 3 shows one b-r color (instrumental magnitudes) plot of an UCT observed in GEO given 15 second exposures [3]. Simultaneous data can be used in comparison to laboratory data to provide characteristic information about the object in question. The variation in color is minor and suggests that the same material is illuminated/observable during the time of this observation.

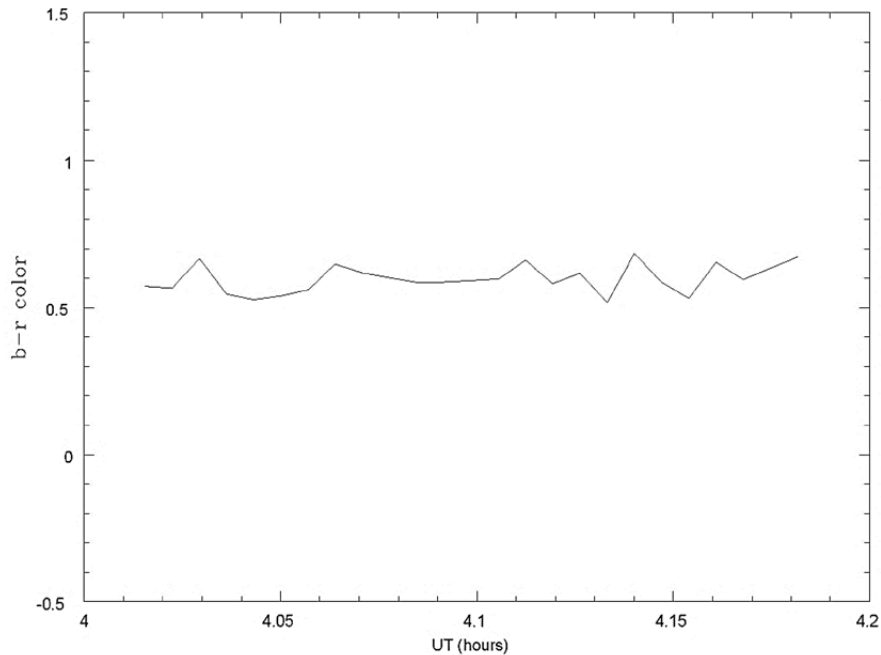


Fig. 3. Simultaneous instrumental color (b-r) for the same GEO object, [3].

2.3 Bi-static Observations

Recent optical campaigns have used MODEST in conjunction with various telescopes to coordinate bi-static observations of specific regions in the GEO. Observing specific targets from two telescopes that are widely spaced can provide information regarding material composition given two different aspect angles relative to the observers with the same sunlit incident angle. To date, MODEST has conducted three bi-static observing runs in collaboration with U.S. Naval Observatory (USNO) 1.3-m telescope in Flagstaff, Arizona. The first bi-static observing campaign was completed 22 February 2014 with 30 minute observations of the same GEO region on 8 different fields. Fig. 4 shows the fields of views of the two observatories and the potential targets viewable by both observatories at 0000 UT. The delta longitude and latitude between the two observing sites are 40.9° and 65.4° , respectively, providing a GEO parallax factor of more than 10° . Sample CCD images from MODEST and USNO of the same observed targets, including Spaceway 1 (2005-015A; SSN 28644), are shown in Fig. 5 and Fig. 6 [4]. Both images have four of the six targets in common; the two targets not shown in Fig. 6 are believed to be hidden in the CCD gaps.

The second bi-static observing run between MODEST and USNO was conducted 24 June 2014 with 30 minutes of observations on selected GEO targets, including high area to mass objects, Wide Area Augmentation System (WAAS) satellites and Intelsat satellites.

The third multi-static GEO observing campaign included participation from MODEST, USNO 1.3-m telescope, 3.5-m Space Surveillance Telescope (SST), and Blanco 4.0-m telescope at CTIO. This observing run was conducted 25 June 2014. Preliminary results of these three runs will be presented in [5].

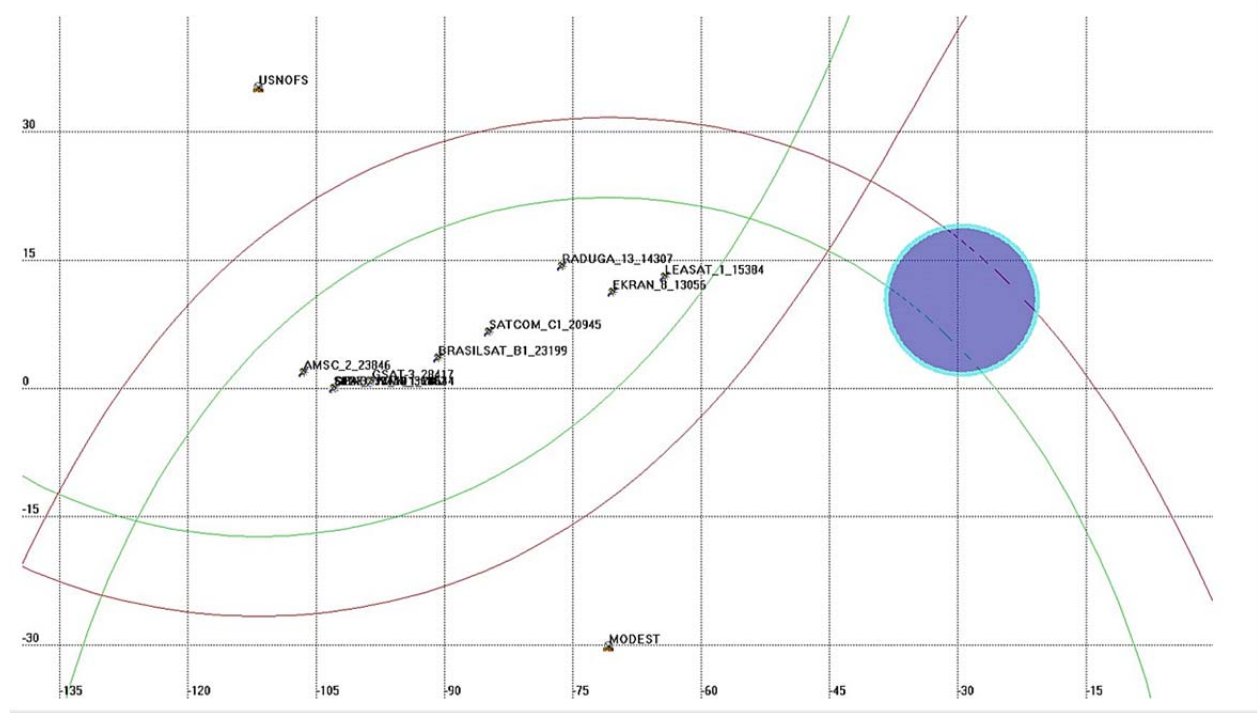


Fig. 4. Simulated observing map for accessible targets from MODEST and USNO, Flagstaff (USNOFS) at 0000 UT on 22 February 2014. X-axis represents West longitude and y-axis represents North latitude. The satellite names are shown, but due to relatively close proximities, some of the target names overlapped. Green lines are the 30 degree elevation limits for GEO objects as seen from each site, red lines are the 15 degree elevation limits. The blue circular area is Earth shadow at GEO (altitude = 35786 km) at the start of the observing window [4].

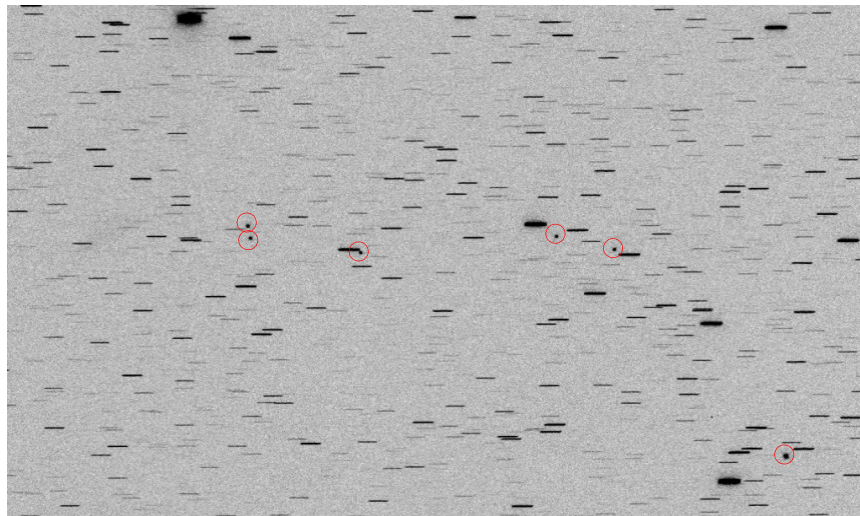


Fig. 5. MODEST image 182 at 02:44:54 UT [4].

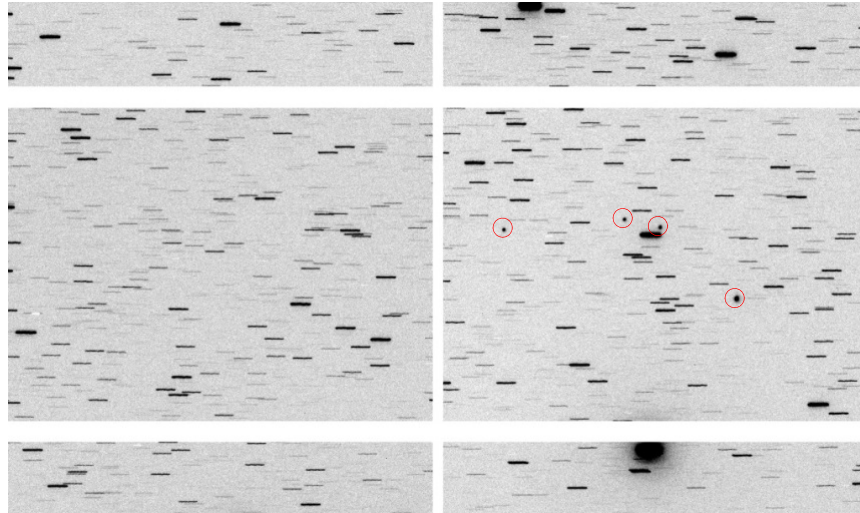


Fig. 6. USNO image 063 at 02:44:30 UT [4].

3. Magellan Telescopes

The twin 6.5-m telescopes (shown in Fig. 7) located at Las Campanas Observatory in Chile have been used to complete deep imaging of the GEO regime as well as providing instrumentation for spectral measurements of GEO targets. Both telescopes are a collaboration of the Carnegie Institution, University of Arizona, Hazard University, University of Michigan, and Massachusetts Institute of Technology.



Fig. 7. Left: Baade used for imaging, Right: Clay used for spectroscopy.

The first telescope used was the ‘Walter Baade’ 6.5-m telescope equipped with the Inamori-Magellan Areal Camera and Spectrograph (IMACS). This instrument has the widest view of view (30' diameter) of the two telescopes/instrument combinations and uses 8 blue sensitive E2V CCDs. This telescope allows for faint debris detections and has a limiting magnitude of 21 in a 5s exposure compared to MODEST (limiting magnitude of 18). Preliminary data from the March 2011 observing campaign can be found in [6].

The Landon Clay 6.5-m telescope is equipped with the Low Dispersion Survey Spectrograph 3 (LDSS3). Using a 5" slit with a spectral coverage of 3800-9000 Å, various GEO debris targets have been observed and analyzed. The Clay telescope does not have an atmospheric dispersion corrector to compensate for atmospheric refraction, therefore the results are limited to 4000-8000 Å. Results can be found in [7] and [8]. The data are compared with laboratory data to best determine surface material composition for objects observed at different phase angles and

aspect angles. The laboratory measurements are taken at the same relative phase angle, and with no space weathering effects, thus making material correlations challenging when compared with telescopic data of objects that have been in orbit for a significant amount of time. In addition, objects in space may be tumbling and presenting multiple surfaces during each exposure. Further investigation into how to best correlate telescopic data with laboratory data is on-going.

4. Optical Measurement Center

4.1 Photometry

To better characterize and model optical data acquired from ground-based telescopes, the Optical Measurements Center (OMC) at NASA/JSC attempts to account for the noted differences between laboratory and telescopic data by emulating illumination conditions seen in space using equipment and techniques that parallel telescopic observations and source-target-sensor orientations. Equipment in the OMC includes a 75-watt Xenon arc lamp, used as a solar simulator; a Santa Barbara Instrument Group CCD camera with standard Johnson/Bessel filters; and a robotic arm, used to simulate an object's position and rotation. Fig. 8 shows a schematic diagram of the laboratory set-up. With a rotary arm that holds the illuminator, the OMC can access 0° - 360° phase angles (angle defined as the vertex between source-object-detector). More details on the instrumentation and data collected are available in [9].

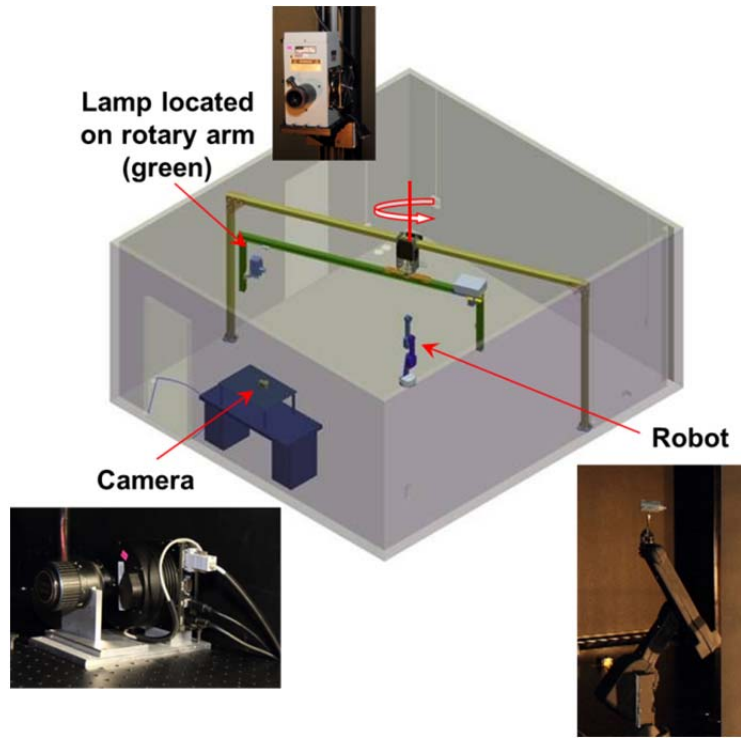


Fig. 8. OMC layout with major instrumentation.

Prior to 2014, the majority of data collected used the wrist rotation of the robotic arm to rotate objects along specific axes, depending on how the target was mounted. For example, scaled rocket body measurements required remounting the target three ways to measure: (a) spin-stabilized rotation (about the long axis), (b) end-over-end rotation, and (c) a 10° wobble about the center of mass [10]. Although this information was very useful in analyzing telescopic data to determine how various LEO targets were rotating as compared with laboratory data, it did require remounting the target and repeating all measurements. Remounting the target is not only time consuming, but trends towards lack of repeatability. The most recent upgrade to the laboratory equipment invokes programming the robotic arm to sample the maximum points accessible with a five degree of freedom robot to acquire an object's bidirectional reflectance distribution function (BRDF). The robotic control program reads in joint angles via spherical coordinates (θ, ϕ) to manipulate the joints to maximize the accessible positions ($\theta_{\max} = \pm 60^{\circ}$, $\phi_{\max} = \pm 360^{\circ}$). The configuration will be the first of its kind to use a broadband light source, rather than a laser, and a photometric detector to calculate a spacecraft material's photometric response via BRDF measurements.

4.2 Spectroscopy

In order to better characterize an object's material composition spectral measurements were acquired. The fine resolution of spectral data acquired at one phase angle can be integrated to specific bandpasses to compare with optical filter photometry for material characterization. An Analytical Spectral Device (ASD) field spectrometer with a range from 300-2500 nm and a resolving power of approximately 200 (corresponding to a bandwidth of 10 nm at 2000 nm) and 717 channels has also been employed to obtain baseline spectral data on various material types. The system only needs 210 channels in order to obtain the desired bandwidth/spectral resolution, so using 717 channels is over-sampling. Measurements are acquired by placing the target under the quartz lamp illuminator and orienting the spectrometer's fiber feed (mounted in a pistol grip) approximately perpendicular to the target surface. Depending on the reflectance properties of the target/material, the angle of incidence and detector direction are modified to best sample the material with maximum signal and without saturating the system. The data are output to a laptop computer and reduced using in-house developed software to provide the absolute spectral reflectance. The processed data are uploaded to the NASA JSC Spacecraft Materials Spectral Database, [11]. Access to the database can be acquired via consent of NASA ODPO.

The most recent spectral data acquired were in support of the SpinSat Satellite. More detailed information on this satellite can be found in [12]. The primary goal for obtaining pre-flight spectral measurements is to characterize the main surface materials on the spacecraft, as they have the highest probability of detection from optical ground-sensors based on surface composition. Both materials investigated were composed of Aluminum 6061-T6; IAW MIL-A-8625F, Type II Class 2, a black coating, and chemical conversion coat IAW MIL-C-5541, Class 3 "Gold irridite". Due to the constrained area to work with, the fiber optic detector was held by hand to allow for the maximum reflectance without saturation for spectral characterization. Fig. 9 shows an example of how the instrumentation was set-up.

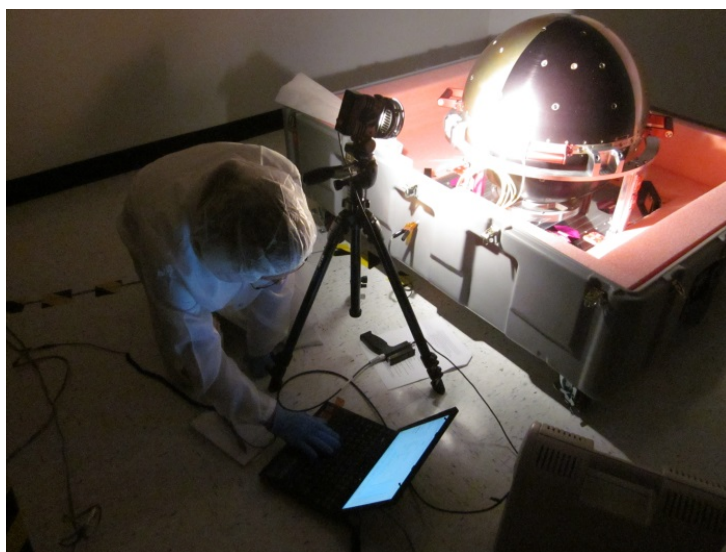


Fig. 9. Spectral measurement set-up for SpinSat

Standard procedure requires a minimum of three spectral measurements to be acquired for each material investigated. In Fig. 9, an average of 8 measurements were taken for each material. The mean is then computed and any outliers (bad/noisy measurements) are discarded. Fig. 10 shows the mean measurements for the gold and black Aluminum surface materials, both scaled between 0 and 1, where 1 indicates 100% absolute reflectance as a function of wavelength in nanometers. The IAW MIL-A-8625F, Type II Class 2 is plotted in red and referenced as "Black" and the chemical conversion coat IAW MIL-C-5541, Class 3 Gold irridite is referenced as "Gold." The aluminum feature is present in both materials centered near 820 nm with a spread from 600 nm to 1000 nm and is more pronounced in the Gold material. The small features (waviness of the line) in the Gold between 600-800 nm are due to the coating used on the spacecraft. For the gold irridite material, the absorption feature centered at 400 nm is indicative of the gold color. The black aluminum is featureless in the visible spectrum, from 350 nm to ~630 nm, due to low reflectance and light being absorbed in this region. Both materials are non-organic; organic features

associated with oxygen-hydrogen bonds and carbon-hydrogen bonds would be present near 1500 nm and 2100-2300 nm, but are not observed.

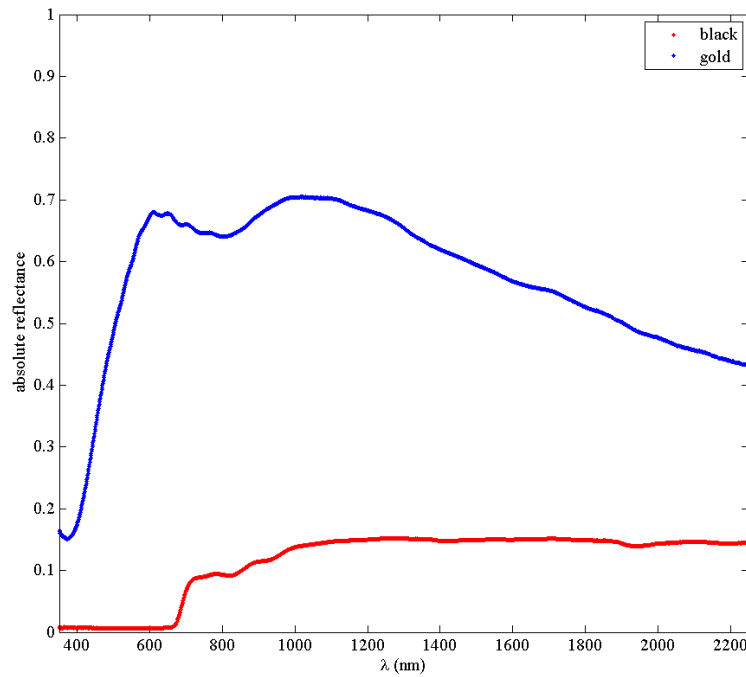


Figure 10. Spectral measurement results from the two primary surface materials on SpinSat.

5. Meter Class Autonomous Telescope

The Meter Class Autonomous Telescope (MCAT) is a joint project with NASA ODPO and Air Force Research Labs. The optical sensor will be dedicated to observing GEO as well as Middle Earth Orbit (MEO) and LEO orbital debris. MCAT is a 1.3-m telescope manufactured by DFM Engineering, which features a fast tracking Observa-Dome and a 4Kx4K SI camera with an 8 position filter slide housing Johnson/Bessell B,V,R,I and Sloan Digital Sky Survey g' , r' , i' , z' , filters. Details of the telescope and related hardware/software can be found in [13].

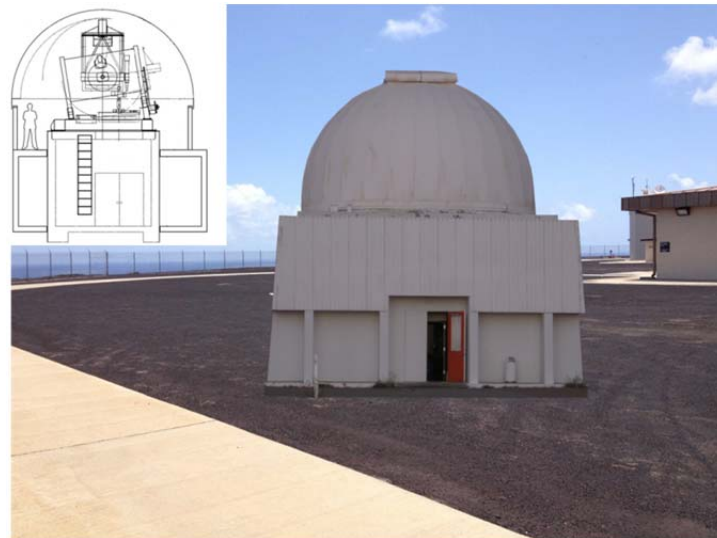


Figure 11. Vision of MCAT located at the Consolidated Instrumentation Facility (CIF) on Ascension [13].

MCAT has passed several recent milestones, including the Critical Design Review, preliminary Observatory Control Software (OCS) acceptance testing, and shipping all instrumentation and hardware to Ascension Island as of early July 2014. Ground-breaking is scheduled for late August/early September 2014. The OCS will also control the Differential Image Motion Monitor (DIMM) seeing monitor to be co-located with MCAT. The instrumentation for the DIMM is currently undergoing integration testing to fulfill the project's requirements. Full site acceptance testing is scheduled for summer 2015 with first light occurring around the same time frame.

6. Summary

Multiple ground-based assets have been used to acquire statistical survey data, detect faint debris, acquire photometric and spectroscopic data, and soon detect debris at faster rates than the typical GEO rates of current optical telescopes. Laboratory data are used to better characterize orbital debris via material composition and potential rotation axes.

Using this ensemble of data, ODPO continues to refine the environmental models used to determine the current and historical flux of debris in multiple orbits. These environmental models help drive the goals and direction for observing campaigns. With the limited optical observations for the MEO and LEO regimes, MCAT will be a great asset to the modeling group to fill in gaps where other data are limited.

7. References

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